# THE DEVELOPMENT AND CHARACTERIZATION OF MAGNETOSTRICTIVE TRANSDUCERS

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## INTRODUCTION

A number of metals, when subjected to a magnetic field, exhibit strain if they are free,or stress if rigidly clamped. This phenomenon, magnetostriction, has an inverse effect which leads to a change in magnetization when the metal is stressed. Inverse magnetostriction offers the possibility of application to the transduction of ultrasonic signals into initially magnetic and then electric signals. Considerable work has been carried out on magnetostrictive ultrasonic transducers [1], but little on the development of high bandwidth inverse magnetostrictive (IMS) transducers.

Magnetostrictive detectors, whilst not being able to match piezoelectric devices in sensitivity, may offer advantages in hot environments where it is usual to use a waveguide between the surface and the transducer. The waveguide may be the magnetostrictive element. Furthermore, this waveguide may be part of a rotating component and the pick-up coil could be non-contacting. Magnetostrictive materials such as nickel are easily worked and so transducer resonances and reflections may be more easily controlled by careful design.

## PRELIMINARY DEVELOPMENT OF AN INVERSE MAGNETOSTRICTIVE DETECTOR

The design of any transducer usually involves some compromises. Aperture effects associated with the contact area between the transducer and the surface to be investigated dictate that this be small for a high bandwidth. Magnetic flux changes associated with acoustic waves are measured by a pick-up coil wound on the magnetostrictive material. In its simplest form this suggests the device will be a long thin rod.

The prototype transducer on which initial tests were made is shown in Figure 1. The basis of the transducer is one coil of a small electromagnet with a magnetostrictive metal rod replacing the pole pieces. The electromagnet coil generates a biasing field and a measuring coil and a trigger coil were wound directly onto the test bar. A magnetic disc recorder head was used in early experiments, but found to have a poor signal/noise ratio compared with a simple coil. Acoustic impulses were introduced into one end of the rod using a Hsu/Nielson source [2] or a piezoelectric pulser. Stress transients in the bar give rise eventually

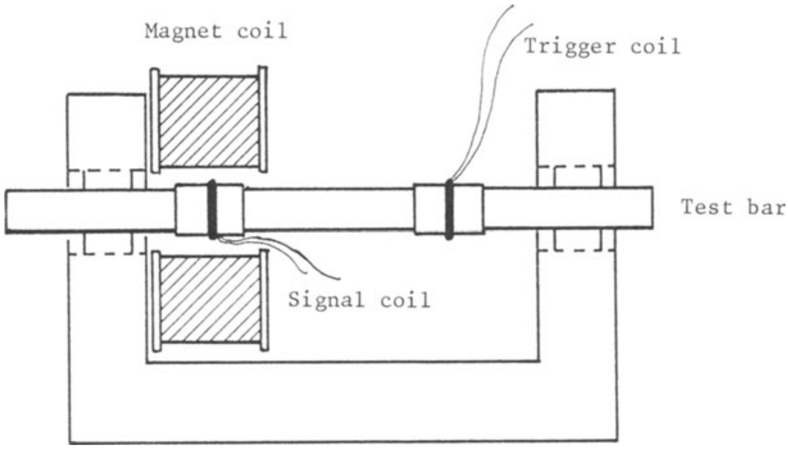


Figure 1 Electromagnet and test bar

to electrical signals in the measuring coil. The various parameters in the transduction process are briefly examined.

(i) Pick-Up Coil and Circuitry

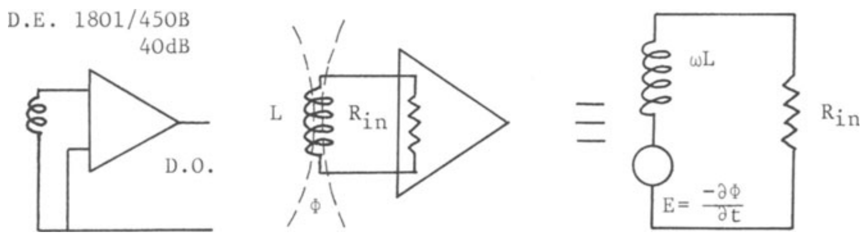


Figure 2 Measuring coil and equivalent circuit

Figure 2 shows the circuit used to detect the induced e.m.f. in the coil. The variables are the dimensions and number of turns (N) of the coil and the input impedance of the preamplifier. Unfortunately, a large N leads to a large inductance and corresponding high output impedance. This means that the input impedance of the preamplifier, $R_{in}$, must be raised correspondingly if high frequency response is not to be reduced. The voltage across $R_{in}$ in Figure 2 is given by: $VR_{in}/(R_{in} + j\omega L)$ where V is the induced e.m.f. in the coil. The experimentally measured S/N ratio for the leading pulse due to a Hsu/Nielson excitation is plotted against N and $R_{in}$ in Figure 3 and the relative response to high frequency components is shown in Figure 4.

In order to explain the results in Figure 3 the different noise mechanisms must be identified. These are: (i) the noise due to fluctuations in charge flow within the amplifier components, (ii) Johnson noise in the input impedance, and (iii) noise associated with large numbers of turns in the coil when shielding becomes ineffective and pick-up dominates.

The total noise voltage, $V_T$, is given numerically by:

$$V_T^2 = (5 \times 10^{-6}) + (0.13 \times 10^{-6} R_{in}^{\frac{1}{2}})^2 + \left(\frac{AN}{\rho}\right)^2 \qquad \ldots (1)$$

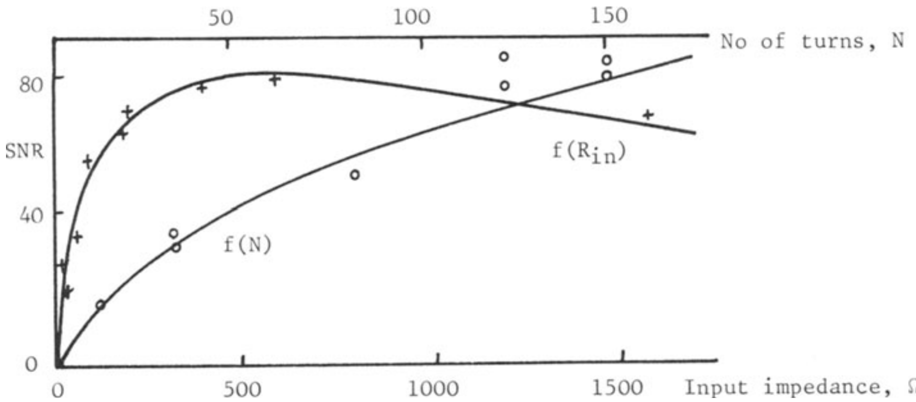


Figure 3 Signal/noise ratio as a function of $N(R_{in} = 100\Omega)$ and $R_{in}(N = 80)$

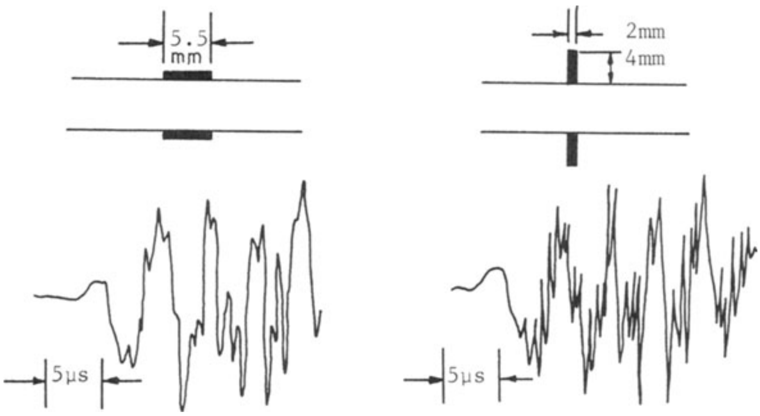


Figure 4 Change in IMS signal with coil dimensions

where 5μV was the experimentally measured amplifier noise, $R_{in}$ is the input resistance and A being a constant of proportionality.

The choice of $R_{in}$ and N determines the upper frequency limit of the device. For impedance matching $R_{in} \propto L$ and for a simple coil $L \propto N^2$ and therefore $N^2 \propto R_{in}$.

Experimental measurements were used to determine the S/N ratio. The particular test signal was a Hsu/Nielson source applied to a 19mm Permendur bar. The first peak of the signal to arrive at the detecting coil was found to be given by:

$$V_s = CN\,(1 + \omega L/R_{in})^{-\frac{1}{2}}\ ,\ C = 2.1 \times 10^{-5}V \qquad \ldots(2)$$

$R_{in}$ and L were chosen so as to make changes in the signal to noise ratio (SNR) significant for the first pulse in Figure 4. The SNR is therefore given by equations (1) and (2) and is:

$$SNR = \left\{\frac{2.1 \times 10^{-5}N}{(5.2 \times 10^{-6})^2 + (AN)^2}\right\}^{\frac{1}{2}} (1 + \omega L/R_{in})^{-\frac{1}{2}}$$

Figure 3 has this form where $\omega L/R_{in}$ is constant.

The upper frequency of the leading pulse is $\sim$ 65kHz and so for $R_{in} > 200\Omega$ the factor $(1 + \omega L/R_{in})^{-\frac{1}{2}}$ is negligible when N = 80, giving rise to a SNR of the form $A(B + R_{in})^{-\frac{1}{2}}$. However, for small values of $R_{in}$ the opposite is true, so SNR $\propto R_{in}(\omega L)^{-\frac{1}{2}}$ in good agreement with Figure 4. The values of $R_{in}$ and N determine both the absolute noise figure and the frequency response and should be chosen with care to produce a wideband device with maximum SNR. If $A_p$ can be made zero, corresponding to perfect shielding, the signal to noise ratio over the frequency range 0 to 2MHz for N = 150 is 190 . The SNR for a piezoelectric transducer mounted on the far end of the Permendur bar (the metal with the largest magnetostrictive coefficient used here) is approximately five times greater in terms of linear voltage response.

Finally, the coil shape must be considered. In the case of a short coil (Figure 4), the high frequency ($\sim$ 1MHz) components are approximately doubled in amplitude.

It is clear that the signal to noise ratio and the electrical frequency response are controlled by the number of turns and the input impedance of the preamplifier. The optimum N is around 250 with $R_{in}$ equal to 20k$\Omega$. A coil with these parameters has been constructed in such a way that high frequency information is preserved.

### (ii) Choice of Magnetostrictive Material and Biasing Field

Several materials have usable magnetostrictive coefficients, the most promising being 49-Permendur (49% cobalt, 49% iron, 2% vanadium). The magnetostrictive coefficient, $\Lambda$, is defined as the strain at magnetic saturation. The value of the coefficient is $+7 \times 10^{-5}$ for Permendur and $-3.3 \times 10^{-5}$ for nickel.

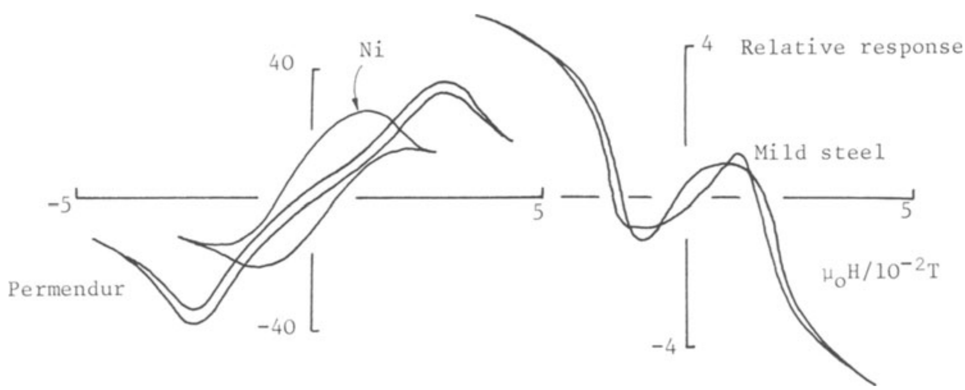


Figure 5 IMS response to first acoustic pulse

The relative response of Permendur, nickel and mild steel to fast acoustic transients was measured as a function of biasing magnetic field, Figure 5. Mild steel, which is also magnetostrictive, was chosen because of its cost and ease of application. As expected, Permendur has the highest response but nickel is a possible candidate for a practical transducer where the response is quite large at zero biasing field due to the high remanent magnetization of this material. The variation of pulse shape with biasing field was also investigated. It appears that Permendur biased at $2.5 \times 10^{-2}$T is the best choice of material.

## (iii) Eddy Current Effects

When a ferromagnetic material is subjected to an alternating magnetic field, eddy currents flow in the material surface. If the rate of change of the field is high these eddy currents create a magnetic field of sufficient strength to shield the inner material from the externally varying field. The reciprocal effect, where a magnetic field generated in the body of the material by inverse magnetostriction leads to eddy currents which in turn reduce the signal in the pick-up coil, is clearly important. A simple method of estimating the effects of eddy currents is to measure the inductance of a measuring coil. It may be shown that the inductance, L, is given by:

$$L = (\mu_r A_{eff}/A_o)L_o \qquad \ldots (3)$$

where $L_o$ is the inductance of the coil alone, $\mu_r$ is the differential permeability at $H = 0$ and $A_{eff}$ and $A_o$ are the effective area of the coil reduced by skin effects and the geometric area of the coil respectively. $A_{eff} = 2\pi r\Delta r$ where r is the coil radius and $\Delta r = \alpha\omega^n$ is the skin depth. Equation (3) becomes on taking logarithms:

$$\ell n \left(\frac{\partial\phi}{\partial I}\right) = \ell n \left(\frac{2\mu_r\alpha L_o}{r}\right) + n\ell u(\omega)$$

Experimentally it is found that $n = 0.45 \pm .07$. A detailed treatment of eddy current effects is given by Bozorth [3] which suggests that at high frequencies $n = 0.5$, therefore the inductance measurements above show that eddy current effects limit the volume of magnetostrictive material in use, this volume being that of a layer approximately 10μm thick at the surface of the bar.

It may be possible to increase the volume of the magnetostrictive material which leads to the signal by laminating the bar where the signal to noise ratio will be increased by a factor proportional to the number of laminations.

## (iv) The Bar Diameter

Varying the diameter of the transducer bar affects both the magnitude of the induced signal and the rise time. It has been shown that the magnitude of the IMS signal is proportional to the displacement of the end of the bar. A piezoelectric pulser with a very reproducible output was used with the Permendur rod machined to different diameters. The relative IMS signal is shown in Figure 6 together with the theoretical output calculated by assuming plane waves incident on the transition from the large diameter to the variable diameter section with the pick-up coil. The invariance of the displacement with radius in the reduced part of the bar is confirmed by the results for small radii. At large radii > 6mm the surface of the bar is subjected to small displacements due to the fact that the surface of the rod becomes a nodal surface at $r \simeq 13$mm [4,5].

The effect of bar diameter on the rise time of the IMS transducer was measured using a series of bars of uniform cross section all stimulated by the same pulse, a Hsu/Nielson pencil break. The rise time of the first pulse as a function of bar radius in mild steel is shown in Figure 7. The rise time appears to be proportional to the diameter for large radii, but tends to a constant value as the radius is reduced. The limiting rise time is assumed to be due to the rise time of the Hsu/Nielson source. Measurements with a laser interferometer indicate that the source rise time is approximately 1 - 2μs in agreement with that in Figure 7.

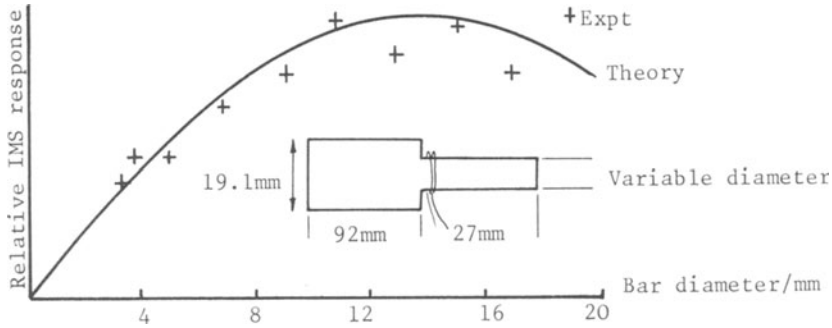


Figure 6 IMS signal as a function of bar diameter

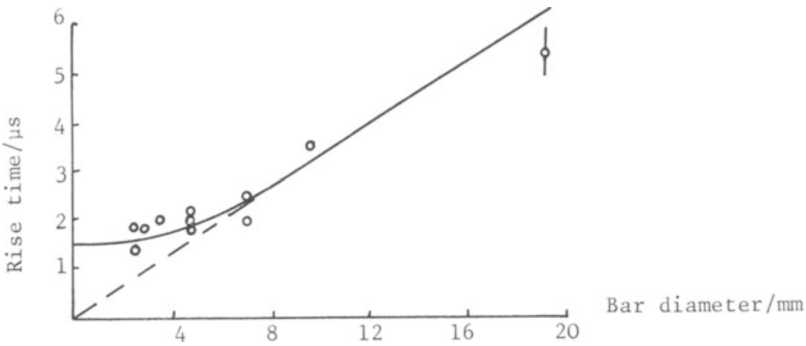


Figure 7 Rise time of the first peak with bar diameter in mild steel

(v) Magnetic Effects Associated With The Measuring Coil

A number of modelling experiments using a moving short solenoid inside a glass tube were carried out to determine the effect of pick-up coil spacing on signal rise time. In all cases there was good agreement with a theoretical model. Other coil configurations were tested including a differentiating double coil. Although this system leads to higher frequency information it does not make mathematical deconvolution of the signal any easier.

TRANSDUCER DESIGN

The experimental and theoretical modelling of the stress pulse and the associated magnetostrictive signals in the previous section allows a practical transducer to be considered.

The first decision to be made regarding the design of an IMS transducer is the shape of the bar. It has been shown above that due to eddy currents the amplitude of the device response is proportional to the bar radius. A large radius should therefore lead to a high S/N ratio. However, for ultrasonic waves detected off epicentre this would lead to a large aperture effect. A compromise might be to form the tip of the transducer into a truncated cone. However, there is no gain from this as the energy and therefore displacement is reduced as the waves propagate into the large radius section of the bar. These conclusions have been confirmed experimentally and the best bar shape is that of a uniform cylinder. The diameter is a compromise between the smallest transducer aperture and the need to maintain a reasonable S/N ratio.

In order that pulse distortion/dispersion in the bar is minimised, it is clear that the pick-up coil should be near to the contact end and wound directly on the bar. The coil itself should have an induction which is sufficiently low so as to ensure that the input impedance of the preamplifier does not significantly affect the system frequency response. Furthermore, the dimensions of the coil must be small compared with the magnetic effects associated with the acoustic transients. A 300 turn coil was used in the prototype transducer as well as a double coil (2 x 150) mentioned earlier which was used to try to improve the frequency response. 49-Permendur with the highest magnetostrictive coefficient is obviously the best material of those available.

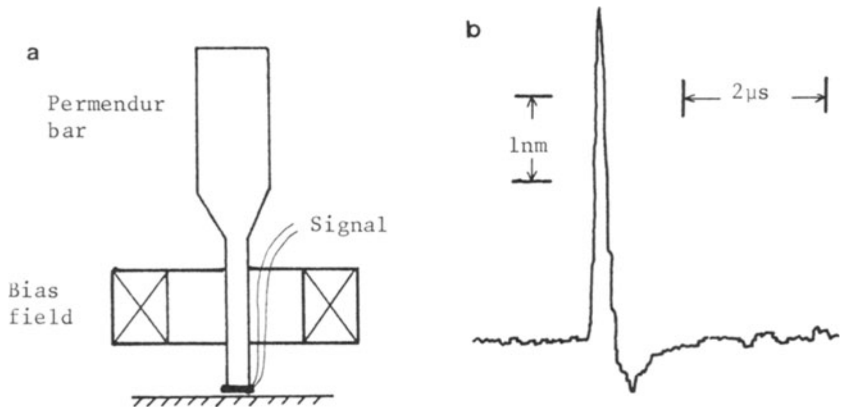


Figure 8
(a) Prototype transducer (b) Surface displacement for calibration

CALIBRATION

The prototype transducer, Figure 8a, was mounted on a large aluminium block and calibration carried out using epicentral and surface wave excitation. Silicone grease was used to couple the end of the Permendur bar to the surface. In the epicentral technique [4] calibration is based on comparing the vertical displacement of the surface of the aluminium block with the output of the IMS transducer mounted on the block which is excited by a broadband ultrasonic transmitter directly below the measuring point. Surface displacements are measured absolutely using a stabilized optical interferometer.

The surface movement of the aluminium block is shown in Figure 8b and the corresponding output of the IMS transducer for both single and double coil configurations in Figure 9. The frequency modulus calibrations are shown in Figure 10. It is clear that the simple coil system has a useful response up to ∿ 3.7MHz whilst the double coil does, as expected, extend further to around 4.4MHz. It must be remembered that the calibration is somewhat approximate due to ringing of the transducer and the finite time window used to capture the trace.

In the case of surface calibration, due to signal to noise problems, the IMS transducer was compared to a broadband piezoelectric detector [6]. This has been shown to have a fairly flat (within 20%) frequency response up to 1.5MHz. The IMS transducer and the absolutely calibrated point contact piezo device were placed symmetrically around an angularly invarient ultrasonic source, in this case a Hsu/Nielson source which has sufficiently high frequency compared with the IMS device which is limited by the aperture of the contact face.

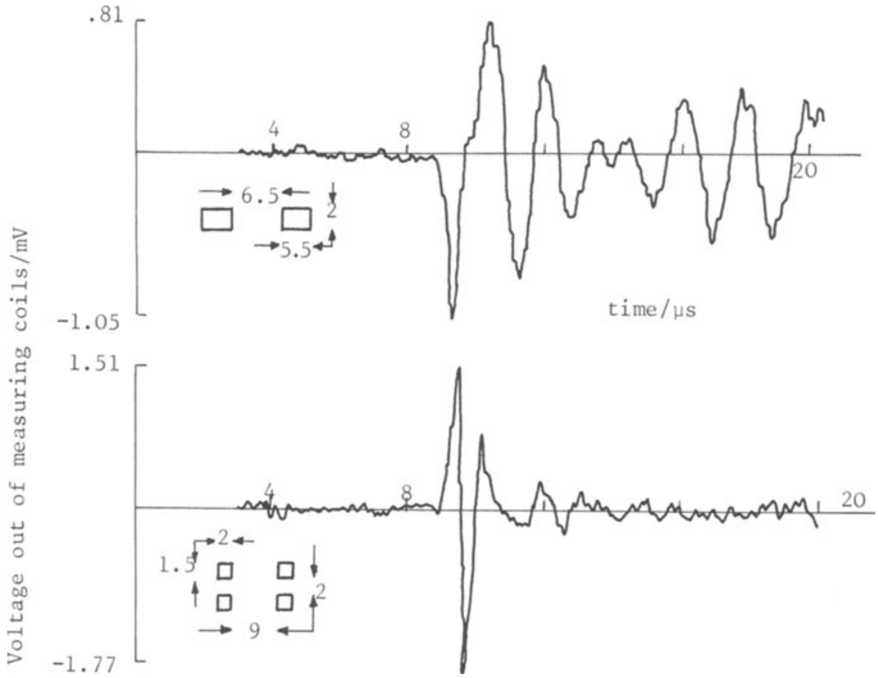


Figure 9 IMS signals corresponding to
the single and double coils

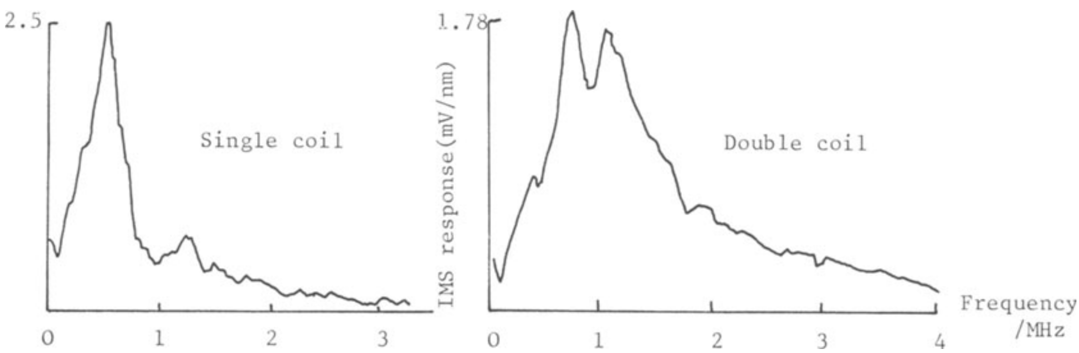


Figure 10 Relative frequency moduli for
the single and double coils

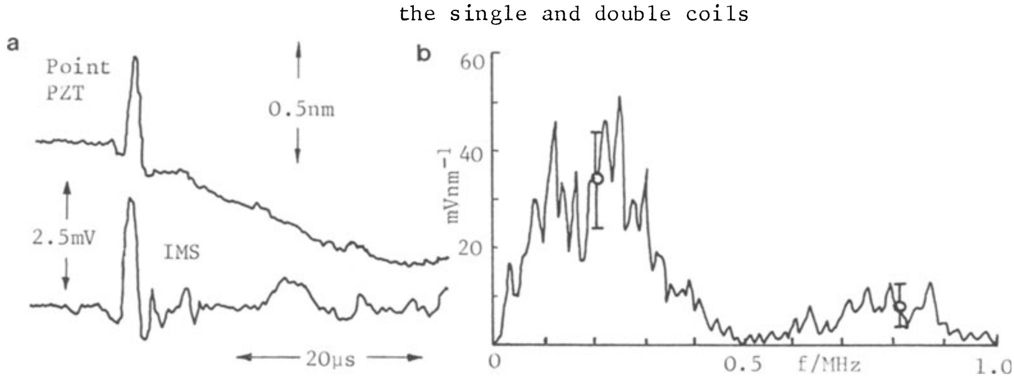


Figure 11(a) Broadband PZT detector and IMS signals
for surface wave excitation
(b) Frequency modulus of IMS transducer

The time domain responses for the two detectors together with the modulus is shown in Fig. 11. Clearly, the frequency response is modified in the surface wave case compared with the epicentral calibration shown in Fig. 10. The difference is thought to be associated with two effects. When the wavelength of the surface wave matches the bar diameter the IMS detector should give no response. This frequency is given by $C/\lambda = (2.906/6)$ MHz = 484kHz. In addition to this aperture effect, dispersion in the transducer bar will result in frequencies around 500kHz being delayed. Although in principle this does not affect the modulus of the frequency response at 500kHz, some reduction is expected because of the finite time window in the Fourier transform process.

## CONCLUSIONS

Consideration of the various parameters in the transduction process in a magnetostrictive bar has led to the design of a practical transducer. The frequency response is found to extend with a useful signal to noise ratio up to 4.4MHz. The signal to noise ratio is only $\sim$ 5x worse than that of a piezoelectric transducer mounted on the waveguide. It may be possible to improve the transducer's performance by laminating the waveguide to overcome eddy current effects. The IMS transducer represents a useful device which should find applications in situations where either waveguides are employed, for example on hot surfaces, (provided the Curie point $\sim$ 10000°C is not exceeded), or where rotating machinery is being monitored. The latter is made possible by allowing the transducer rod to rotate inside a stationary pick-up coil.


## ACKNOWLEDGEMENTS

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## REFERENCES


1. B. A. Wise, Design of nickel magnetostriction transducers, International Nickel Co., New York.
2. A. Nielson, Acoustic emission source based on pencil lead breaking, Rep. No. 80.15, Danish Welding Institute, Glostrup, Denmark.
3. R. M. Bozorth, Ferromagnetism, Van Nostrand Co., Inc., Princeton, 1951.
4. R. G. White, Ultrasonic transducer calibration, Ph.D. thesis, Loughborough University of Technology, 1984.
5. H. Kolsky, Stress waves in solids, Dover Publication, New York, 1963.
6. T. M. Procter, Jr., J. Acoust. Soc. Am. 71, 1163, 1982.


## DISCUSSION

From the Floor: What laser power did you use and what was the coherence length?

Dr. Emmony: We are working with a Hughes 2 milliwatt. Laser coherence length, I don't honestly know.

From the Floor: Was it stabilized?

Dr. Emmony: No, it's not stabilized.

Mr. Buckley: Thank you very much.